Effects of Foundation Characteristics and Building Separation Gap on Seismic Performance of Mid-rise Structures Incorporating Soil-Foundation-Structure-Interaction

By

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I hereby certify that the work embodied in this Thesis is the result of original research and has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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LIST OF PEER-REVIEWED PUBLICATIONS BASED ON THIS RESEARCH

PEER-REVIEWED JOURNAL PAPERS

1. Nguyen, Quoc Van, Fatahi, Behzad and Hokmabadi, S Aslan. 2016. 'The effects of foundation size on the seismic performance of buildings considering the soil-foundation-structure interaction', *Structural Engineering and Mechanics*, Vol. 58, No. 6 (2016), page 1045-1075.

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2. Nguyen, Quoc Van, Fatahi, Behzad and Hokmabadi, S Aslan. 2017. 'Influence of Size and Load-Bearing Mechanism of Piles on Seismic Performance of Buildings Considering Soil–Pile–Structure Interaction', *International Journal of Geomechanics*, Vol. 17, No. 7 (2017), page 04017007-1-22.

   DOI: 10.1061/(ASCE)GM.1943-5622.0000869.

3. Fatahi, Behzad, Nguyen, Quoc Van, and Xu, Ruoshi. 2017. 'The response of mid-rise buildings sitting on pile foundations to seismic pounding'. *International Journal of Geomechanics. (Accepted)*

PEER-REVIEWES CONFERENCE PAPERS

4. Nguyen, Quoc Van, Fatahi, Behzad and Khabbaz, Hadi. 'Three dimensional numerical simulation to predict performance of laterally loaded piles on clay-sand layered slope'. *International Conference GeoMontreal 2013*, Sep-Oct 2013, Montreal, Canada.

5. Nguyen, Quoc Van, Fatahi, Behzad and Hokmabadi, S Aslan, 'Influence of Shallow Foundation Characteristics on Seismic Response of Mid-rise Buildings Subjected to Strong Earthquakes', *International Conference GeoChina 2016*, July 25-27, 2016, Shandong, China, Page 117-124.

ABSTRACT

Seismic waves travel many kilometres and pass through soil layers close to the ground surface before hitting the structures. The seismic induced dynamic behaviour of structures built on soft soil is highly dependent on the soil properties and the foundation type due to their interactions during an earthquake event. The design of building structures needs to consider seismic soil-foundation-structure interaction, where the building responses vary significantly depending upon the fixity of the base condition due to the interaction between the ground and the foundation as well as the building structures. This interaction is called "Seismic Soil-foundation-structure-interaction" (SSFSI). For a typical soil and foundation, SSFSI analysis shows lower natural frequency of the structural system and higher effective damping ratio compared to the traditional analysis with fixed base condition. This can considerably alter the response of the building frames under the seismic excitations by influencing the structural demand of the building as well as amplifying the lateral deflections and inter storey drifts of the superstructure. This phenomenon is highly influenced by the foundation type (i.e. shallow and deep foundation) and may change the performance level of buildings in the performance based design approach. Therefore the interaction should be considered in design of buildings subject to seismic activities so as to provide a safe and cost effective structural system.

In this study, a rigorous numerical modelling approach was developed and used to build numerical tests for different foundation types and sizes as well as the pounding effects between buildings. The results consisted of lateral deformation, inter-storey drifts, levelling shear forces of the structures, foundation rocking, impact force and pile responses. These perimeters cover a wide range of earthquake inputs and foundation characteristics.

The first step was that the soil-pile-interaction numerical behaviour was investigated in a case study of lateral loaded pile considering the shear plastic deformation of the layered sloping ground including sand and clay layers. Appropriate subroutines were adopted to simulate the soil-pile-interaction which included the incorporation of gapping and sliding (in normal and tangential directions) at the interface. A wide range of parameters for this numerical modelling was validated through comparison with an array of a full-scale lateral loaded pile experiments.

Secondly, dynamic characteristics of soil-foundation-structure system were investigated for seismic response of a mid-rise moment resisting building on shallow foundation under four well-known earthquakes. By adopting a direct calculation method, the numerical model can perform a fully nonlinear time history dynamic analysis for three-dimensional numerical model with different foundation sizes where the infinite boundary, sliding and separation in soil-foundation was taken into account. In addition, the influence of foundation sizes on natural frequency and structure response spectrum was also studied. The results confirmed that when the size of shallow foundation is reduced, the natural period would lengthen, the base shear would reduce significantly while the lateral deformation, inter-storey drift and foundation rocking would increase.

Thirdly, the comprehensive pile foundation investigation concludes that the type and size of a pile foundation that supports mid-rise buildings in high-risk seismic zones can alter the dynamic characteristics of the soil-pile-foundation system during an earthquake due to soil-structure-interaction. It is not true to believe that longer piles can provide safer condition under earthquake loading. In fact, by increasing the length of floating piles the structure undergoes more maximum lateral deflection, more inter-story drift and more total maximum levelling shear force but less foundation rocking. This can be explained due to the fact that longer pile foundation has higher contact surface with surrounding soil which enable them to absorb extra seismic energy. This finding can be the recommendation for design engineers that the pile should not lengthen too much to reduce the seismic effects.

Finally, the separation gap between moment resisting and two shear wall braced buildings on pile foundation under seismic loading was studied. The result from this numerical modelling showed that pounding impact influences the distribution of shear force which disturbs the natural vibration and in extreme case, causes collapse. The outcome of this study provides essential insight to geotechnical and structural engineers when designing neighbouring structures in earthquake prone areas.

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LIST OF ABBREVIATIONS

Full text	Abbreviation
American Society of Civil Engineers design code	ASCE
Boundary element method	BEM
Building Seismic Safety Council	BSSC
Complete quadratic combination	CQC
Earthquake design category	EDC
Earthquake Wave Equation Analysis for Piles	EQWEAP
Federal Emergency Management Agency	FEMA
Global Positioning System	GPS
International Building Code	IBC
Linear dynamic procedure	LDP
Linear static procedure	LSP
National Earthquake Hazards Reduction Program	NEHRP
National Computational Infrastructure	NCI
Nolinear dynamic procedure	NDP
Nonlinear static procedure	NSP
Seismic Soil-foundation-structure-interaction	SSFSI
Seismic soil–pile–structure interaction	SSPSI
Single degree of freedom	SDOF
Soil-foundation-structure interaction	SFSI
Soil-pile-structure interaction	SPSI
Soil–structure-interaction	SSI
Structure-soil-structure-interaction	SSSI
Thin layer method	TLM

LIST OF NOTATIONS

$a(t)$	raw data record
$a_c(t)$	corrected acceleration record
$a_0(t)$	acceleration correction
$2a$	width of the foundation
A	Area, foundation width, cohesion
A_{loop}	area of the hysteresis
$[A]$	Damping matrix
B	width of the pile
B_b	width of building
B_f	width of foundation
B_s	width of soil model
c	damping coefficient, soil cohesion
c_h	damping coefficient in horizontal direction
c_θ	damping coefficient in rotation direction
$\widetilde{c}$	equivalent damping coefficient
C_1, C_2, C_3, C_k	modification factor for pseudo lateral load, constant
c'	cohesion, effective cohesion
c_p, c_s	velocities of the normal wave and shear wave
CL	clayey soil
$[C]$	damping matrix
D	diameter of pile
$Drift$	maximum inter-storey drifts of the building
d_p, d_s	distributed damping in the normal and shear directions
d_c	decay coefficient
d_{i+1}, d_i	Deflection at level $(i+1)$ and (i)
$d_i(t)$	deflection history at level (i)
E	Young's modulus, modulus of elasticity of concrete
E_a, E_b, E_c, E_d, E_e	Soil classification according to AS1170.4 (2007)
E_s	soil subgrade reaction
E_p	Young's modulus of pile

E_{x}	soil reaction
F	force
F_{x}	vertical distribution of seismic force at each level
f	natural frequency
f_1, f_2	first and second mode frequencies in Rayleigh damping
f_c'	compressive strength of concrete
f_{n}	natural frequency of mode n
$f_{\mathrm{y}}, f_{\mathrm{sy}}$	yield strength
G	shear modulus, permanent action
G_0	average shear modulus
G_{max}	maximum shear modulus
G_{sec}	secant shear modulus
G_{tan}	tangent shear modulus
H	height of the structure, shear force, soil thickness, soil height
H_s	height of soil model
h	clearance or gap, height of level
h_s	floor slab thickness
h_f	foundation thickness
I	moment of inertia
I_p	moment of inertia of pile
I_x, I_y	moment of inertia about x axis and y axis
IE	bending stiffness of the beam
k	stiffness
k_h	stiffness in horizontal direction
k_i	soil resistance in segment (i)
k_y	lateral stiffness
k_θ	stiffness in rotation direction, rocking stiffness
$\widetilde{k}$	equivalent stiffness
$\overline{k}$	stiffness of the structure fixed at the base
$[K]$	stiffness matrix
L	length

L_b	length of building
L_f	length of foundation
L_{FE}	length of finite element section
L_{INF}	length of infinite element section
m	mass
M	bending moment
$[M]$	mass matrix
M_w	moment magnitude of earthquake in Richter scale
P	lateral load
p	load, contact pressure
p_i	load in segment (i)
P_0	amplitude of harmonic force
P_x	axle force from structure applied to pile head
PI	plasticity index
PGA	peak ground acceleration
q_s	lateral distributed load from soil to the pile
q_y	lateral distributed load along the beam
Q	Impose Action, shear force along the pile
R_{int}	reduction factor
r_{in}	inner radius of the pile
r_{out}	outer radius of the pile
$SDOF$	single degree of freedom
S	slope (or rotational deflection) of the pile, distance
S_a	response spectrum acceleration, spectral acceleration
S_{DS}	design earthquake motion
s_i	minimum distance between adjacent structure at level (i)
S_u	undrained shear strength
$(S_u)_{soil}$	undrained shear strength of soil
$[(S_u)_{int}]$	reduce shear strength at the interface
SD	separation gap
Δ	lateral deflections in $P-\Delta$ effect
Δ_{i1}, Δ_{i2}	lateral deflections of neighbouring structures

T	fundamental period
$\widetilde{T}$	effective fundamental period
T_0	characteristic period of the response spectrum
T_1 and T_2	limits of a time interval
t	time
u_0	structural distortion
u_t^0	total initial lateral displacement
u_t	total lateral displacement
$\widetilde{u_g}$	equivalent input motion
u_i, u_j	material particle displacement
$u_i(t)$	horizontal displacement history at level (i)
$u_0(t)$	horizontal displacement history at level (0)
$\ddot{u}_i$	material particle acceleration
V	pseudo lateral load, shear force
V_S	shear wave velocity
V_{S0}	average shear wave velocity
$v_c(t)$	corrected velocity record
W	total dead load and anticipated live load
$\overline{W}$	total dead load and anticipated live load of structure fix at base
W_D	dissipated energy
W_S	the maximum strain energy
x_i	position of pile at segment (i)
Y	deflection, pile deflection
y_i	deflection in segment (i)
z_i	depth of soil at segment (i)
α, β	mass damping coefficient and stiffness damping coefficient
γ	shear strain, unit weight
$\dot{\gamma}_1$ and $\dot{\gamma}_2$	two local slip velocity components
γ_c	cyclic shear strain, shear strain
γ_{max}	maximum shear strain
$\dot{\gamma}_{eq}$	equivalent slip rate
ε	strain of concrete material

ε_{yield}	strain at yield point
Z	damping ratio
Θ	angle
μ	coefficient of friction
μ_r, μ_p	residual coefficient of friction, peak coefficient of friction
ν	Poisson's ratio
ξ_0	hysteretic damping
Ξ	damping ratio
$\widetilde{\xi}$	equivalent damping ratio
ρ	density, mass density
σ, σ'	normal stress, effective normal stress
$\sigma_{\mathrm{y}}, \sigma_{yield}$	yield stress of concrete material
τ	shear strength
τ_1 and τ_2	two orthogonal components of shear stress
τ_{cr}, τ_{crit}	critical shear stress
τ_{eq}	equivalent shear stress
τ_c	shear stress
φ, φ'	internal frictional angle, effective internal frictional angle
ψ	dilation angle
ω, ω_0	natural frequency
ω_i, ω_j	natural angular frequency for mode (i) and (j)
$\widetilde{\varpi}$	equivalent natural frequency
$\phi, \emptyset$ and $\emptyset'$	friction angle and effective friction angle